Can disks form deuterium burning planets by core accretion?

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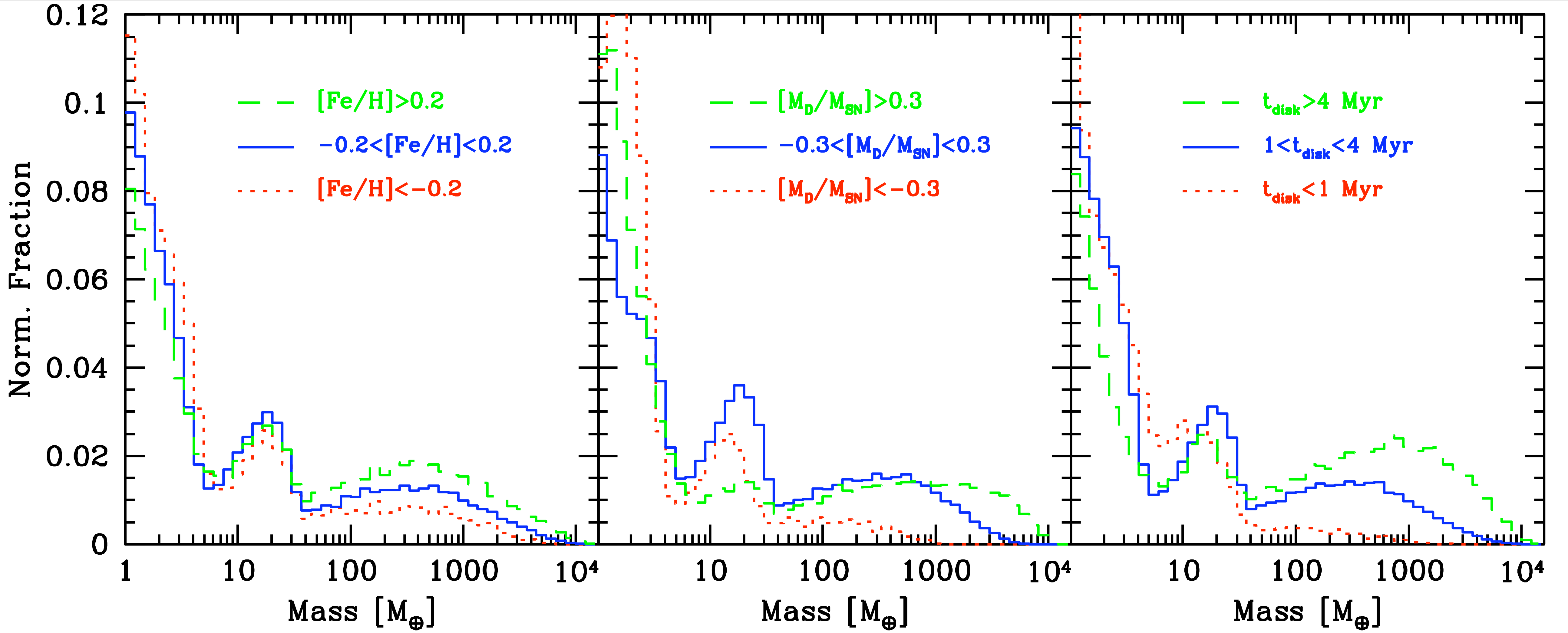
Garching, 6.11.2009 From circumstellar disks to planetary systems

Correlations with Disk Properties

Std. case
M_I=1 M_{sun}
α=7x10^{-3}
f_I=0.001

Metallicity (disk) (dust-to-gas ratio) *Disk mass (gas)* *Disk lifetime*



- *High [Fe/H]:*
  - *higher number of giants (observed)*
  - *but not more massive (except for most massive)*
- *Minimal dependence for Neptunes*
- *Inversion at low masses: Distinguish detectable vs. actual existing planets!*

Disk mass changes the MF shape for giant planets.
High disk mass: giant planets of higher mass, but less of lower mass.

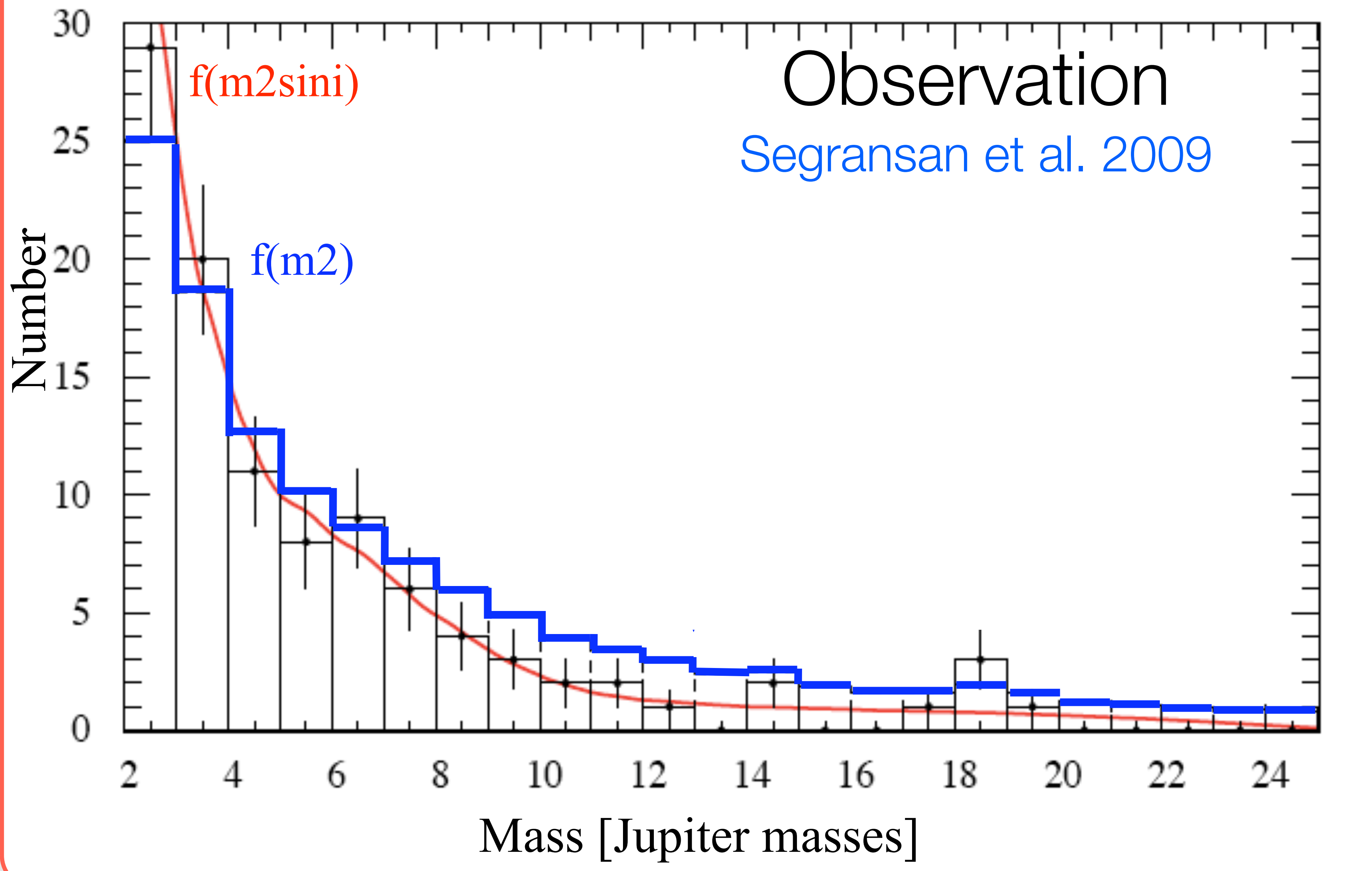
Disk lifetime changes both. Long living disks: giant planets are
- *more numerous and*
- *of higher mass*

-Correlation with M_D

Many more correlations!

Mordasini et al. in prep

Upper End "Planetary" Mass Distribution



- *Rare, but there is a long tail of planets with masses clearly larger than 6-10 M_J.*
- *This are not (all) stellar companions nearly face-on.*
- *No discontinuity: smooth continuation.*
  - *low numbers...*
  - *high mass tail of same formation mechanism?*

Jupiter mass planets: formation by core accretion.
What about these more massive objects?

Maximal Planet Mass - Gas Accretion

Low Mass Planets (M<30-100 M_{earth})

Limited by the planet itself, i.e. its ability to radiate away the energy released through the gravitational contraction of the gaseous envelope (Kelvin-Helmholtz timescale).

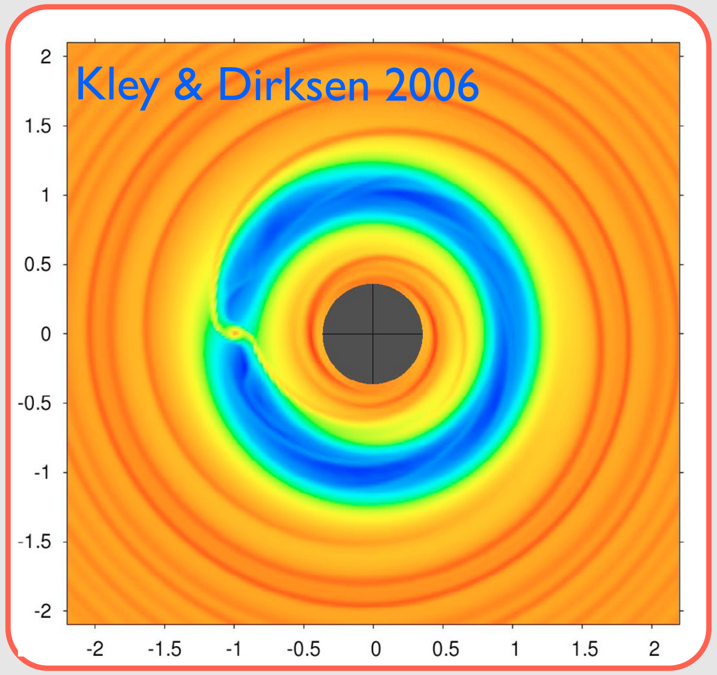
$$\frac{dM_{\rm p,g}}{dt} \simeq \frac{M_{\rm p}}{\tau_{\rm KH}} \qquad \tau_{\rm KH} \simeq 10^9 \left(\frac{M_{\rm p}}{M_\oplus}\right)^{-3} \text{ years.}$$

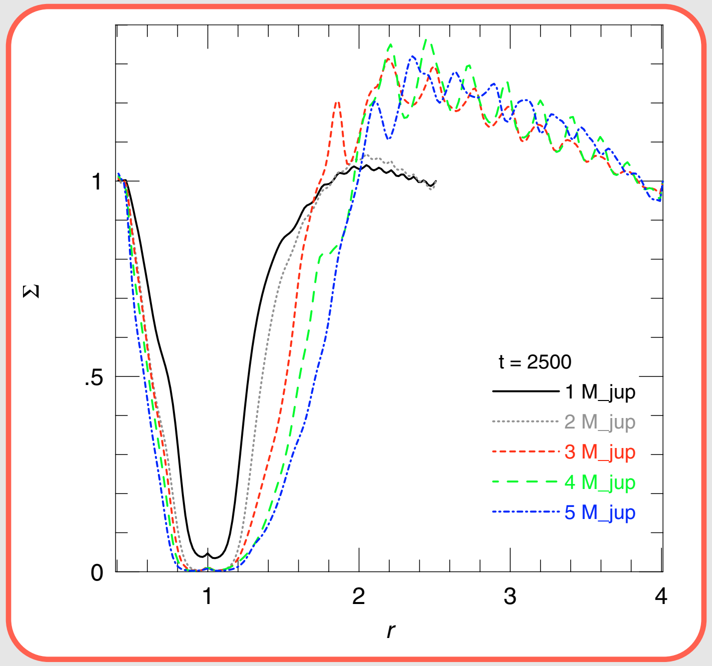
High Mass Planets (M>30-100 M_{earth})

The planet structure takes whatever the disk can feed. Limitation by global effects (disk dissipation, viscous transport to the planet) and/or local gas depletion (gap formation).

Obviously, cannot grow larger than total (late) disk (<0.1 $M_{star} \approx 100\ M_J$)

Limitation By Gap Formation

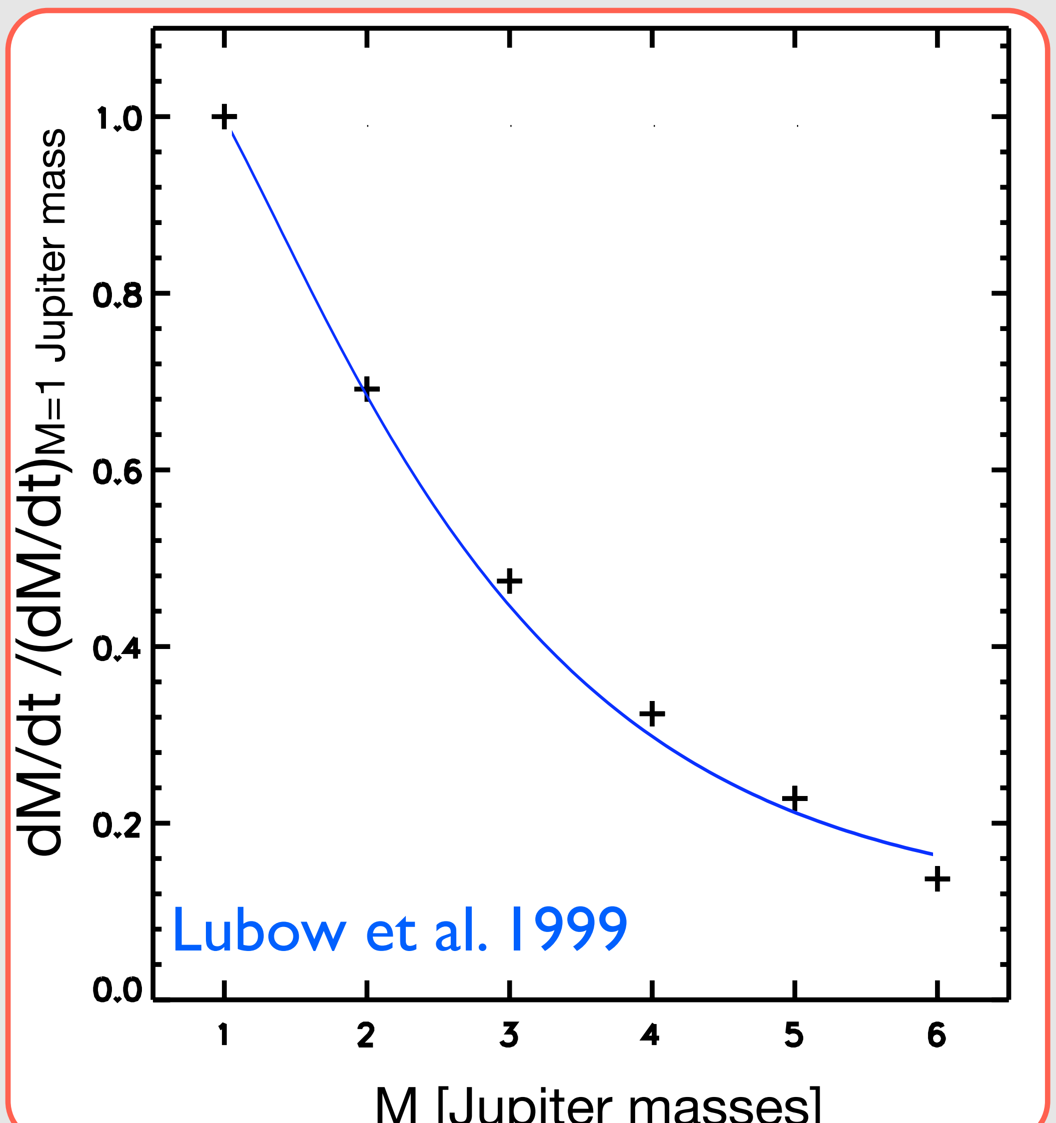




Gap width increases with planet mass.

Gap width increases relative to size of Hill sphere.

"Classical" self-limitation to 6 - 10 M_J for planets.



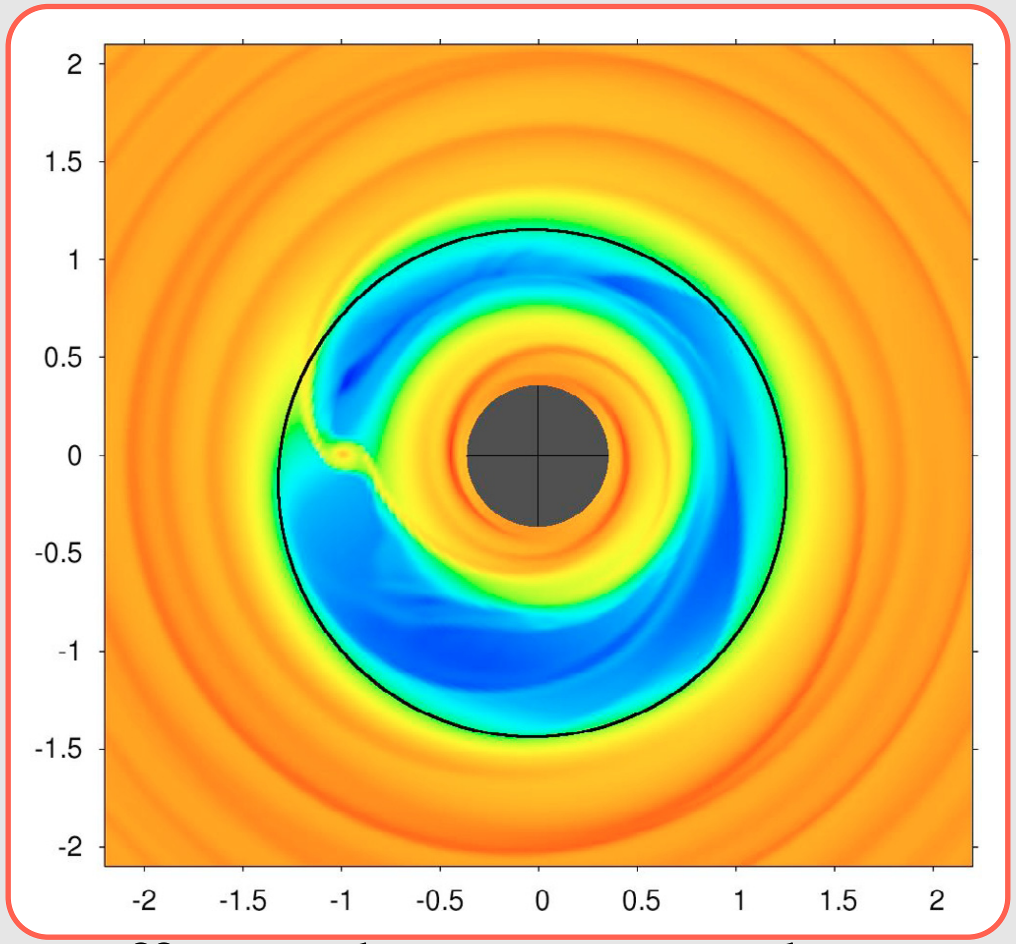
Veras & Armitage 2004

$$\frac{dM_{gas}}{dt} = \dot{M}_{disk}\left(1.668\left(\frac{M_p}{M_J}\right)^{1/3} e^{-\frac{M_p}{1.5M_J}} + 0.04\right)$$

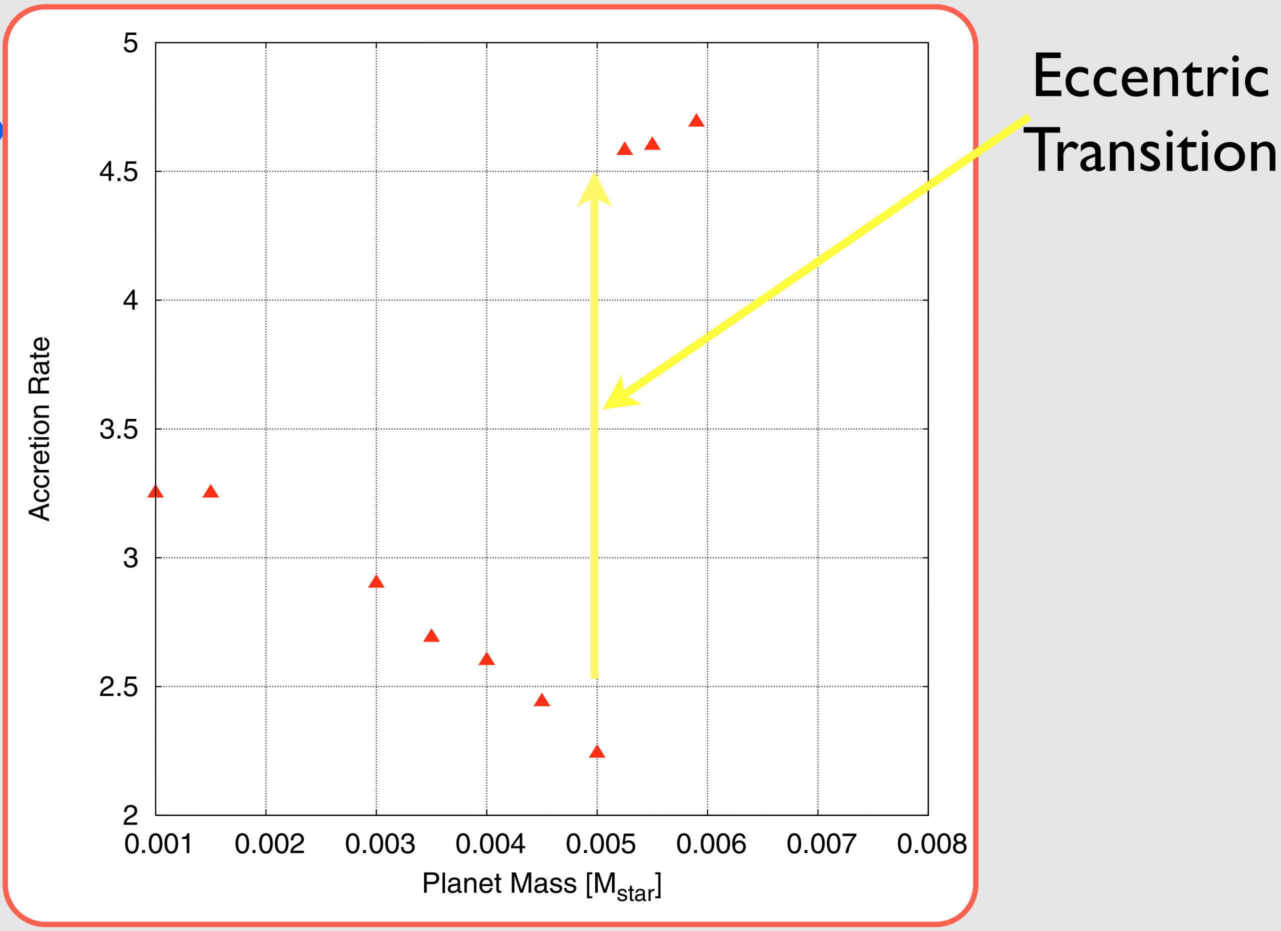
Disk accretion rate

Exponential decrease

NO Limitation By Gap Formation ?



Kley & Dirksen 2006



Sufficiently massive planets (>3-5 M_J) can cause a sudden transition of the disk state from circular to eccentric.

- *Eccentricity excitation at 1:3 outer Lindblad resonance is no more damped at 1:2 for sufficiently wide gaps, i.e. massive planets.*

See also Papaloizou et al. 2001

Mass accretion onto the planet resumes strongly again. Maximum (on longer timescale) is:

$$\frac{dM_{gas}}{dt} = \dot{M}_{disk}$$

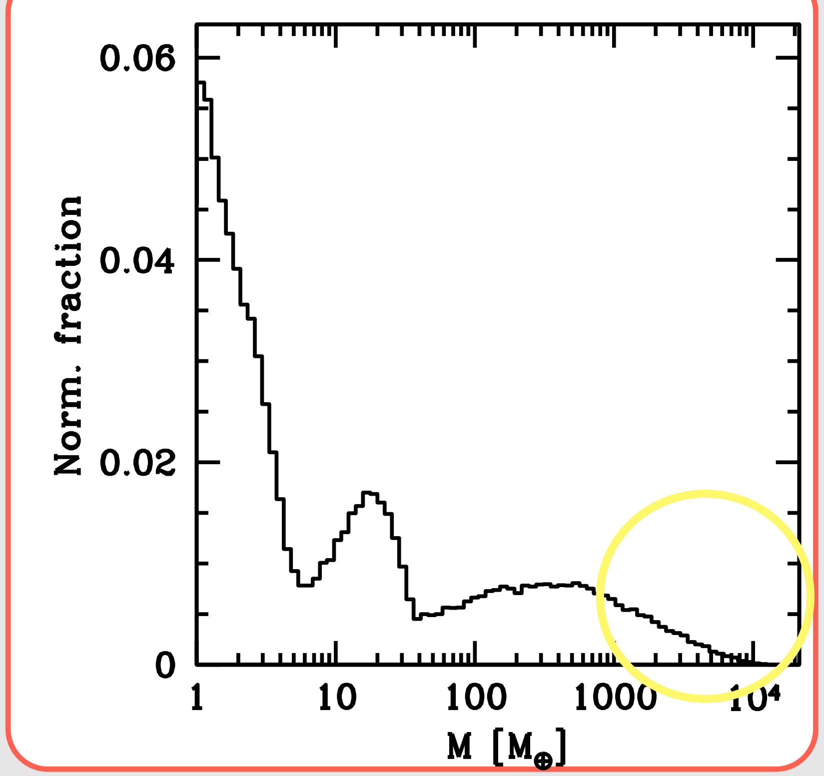
(Disk accretion rate)

Test Global Consequences

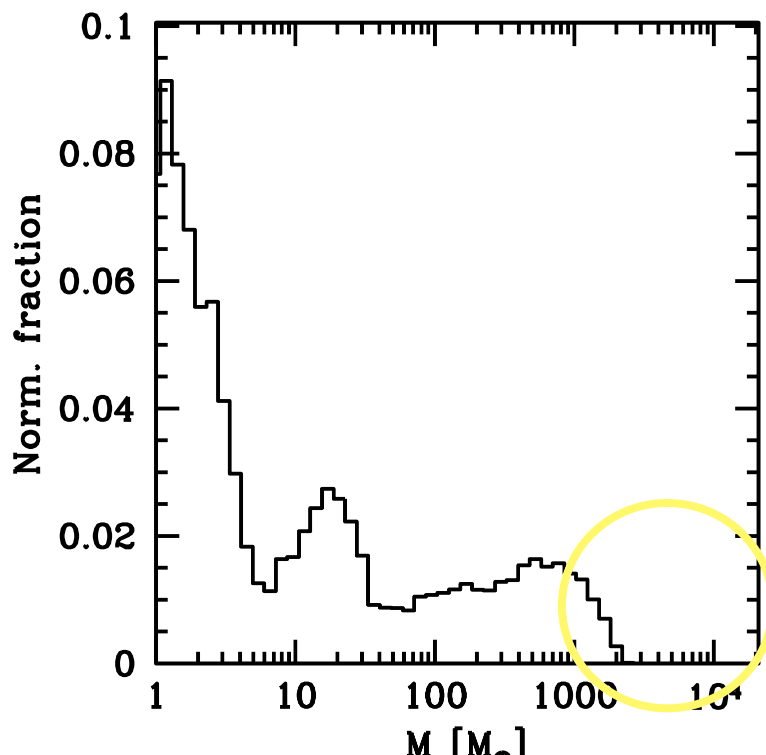
Mstar=1 Msun
f_1=0.001
No irradiation

Planetary IMF

No limitation due to gap formation.
"Extreme Kley-Dirksen way"

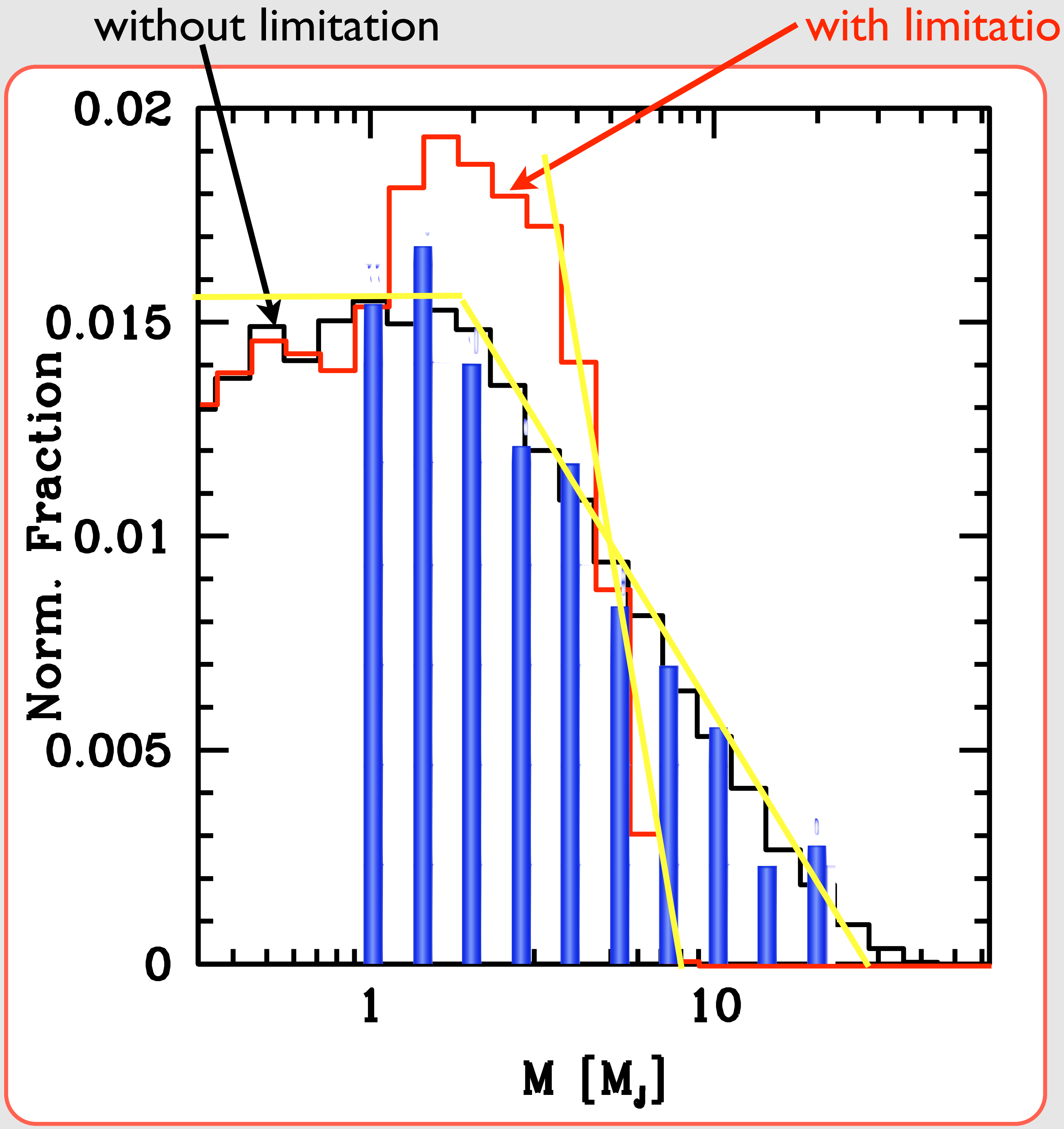


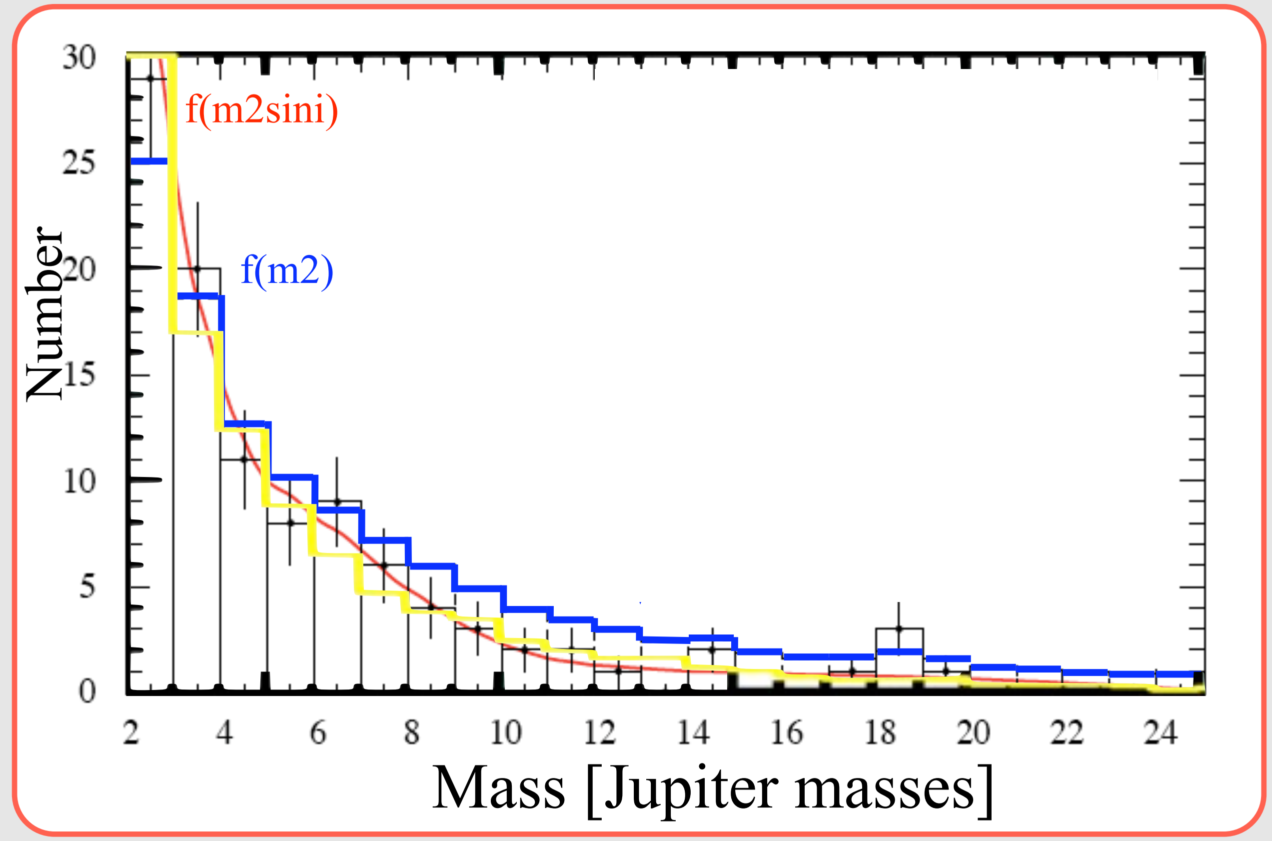
With limitation
"Lubow et al. way"



As expected, strong influence for planets ≳ 6 M_J

Planetary Initial Mass Function - High End





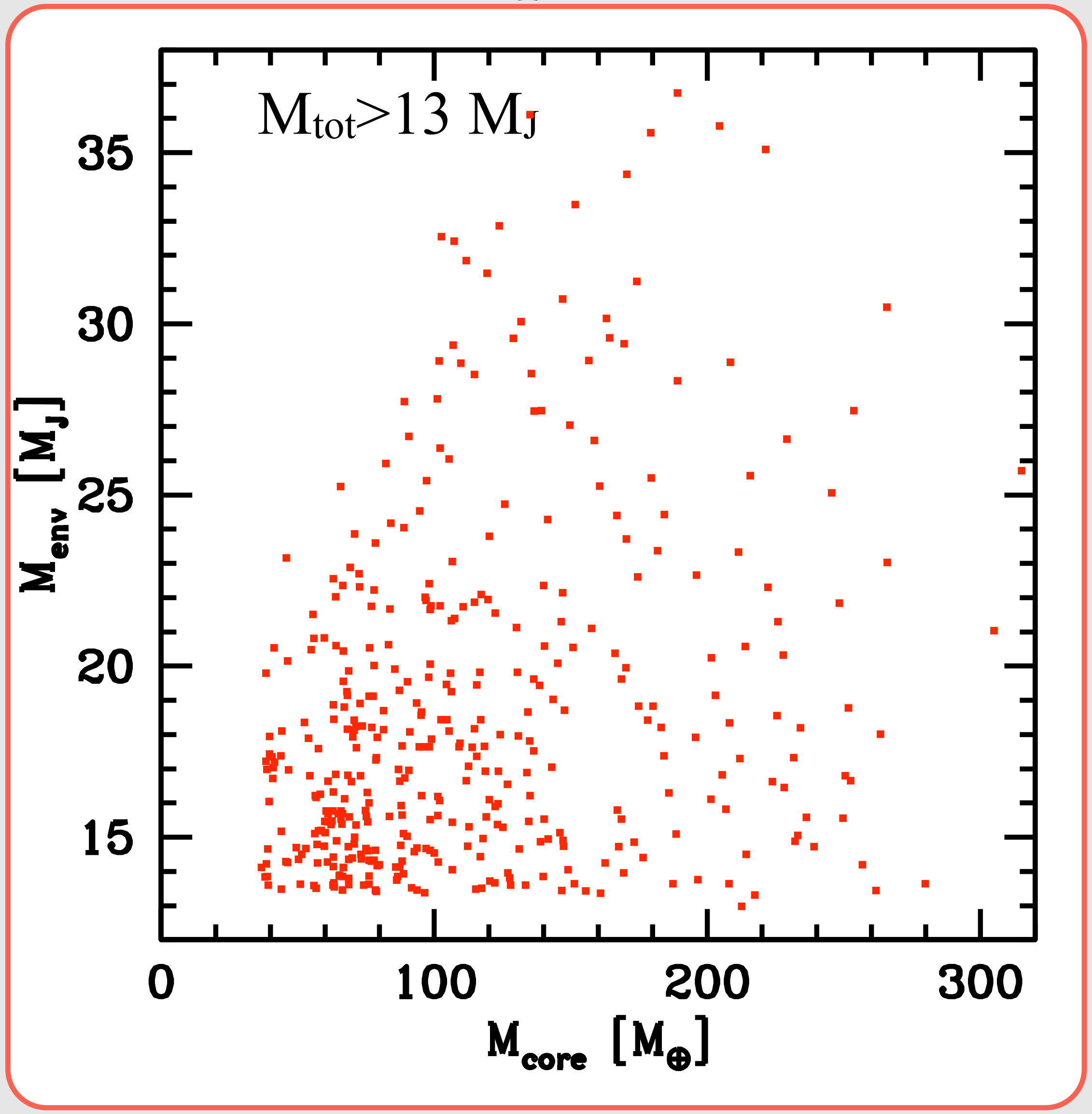
Without dM/dt limitation, $\lesssim$ 0.4% larger than 13 M_J, with limitation, none.

Different slopes: better agreement without limitation.

Rare, but there are now objects above the conventional planet - brown dwarf limit. Nature?

Nature of the Objects

Internal composition



Core masses typically 100 M_{earth}, up to 300 M_{earth}.

Pressure and temperature high enough in layers above the core to burn deuterium ?

Baraffe, Chabrier & Barman 2008

"… We have considered a 25 M_J planet with a 100 $M_\oplus$ core. Independently of the composition of the core material (water or rock), deuterium-fusion ignition does occur in the layers above the core. … The same conclusion holds for a core mass of several 100 $M_\oplus$. …"

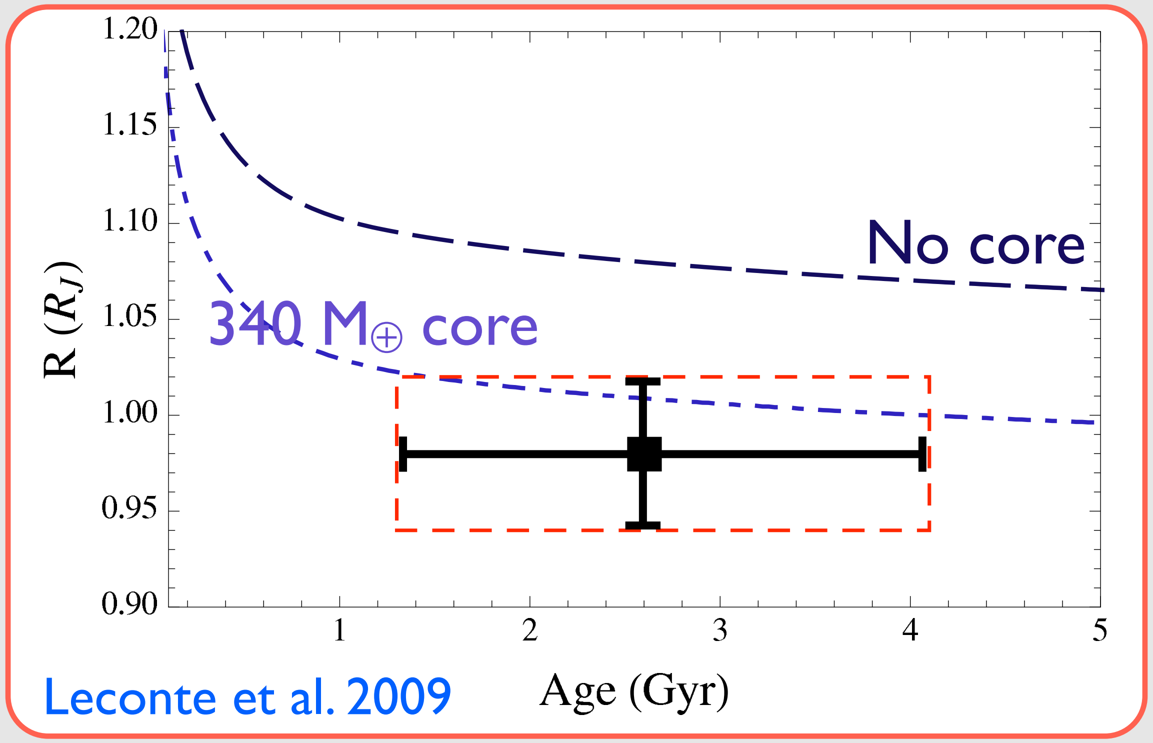
Deuterium Burning Planets

New class of transition objects: Burn deuterium (like brown dwarfs), but have a formation and composition like planets.

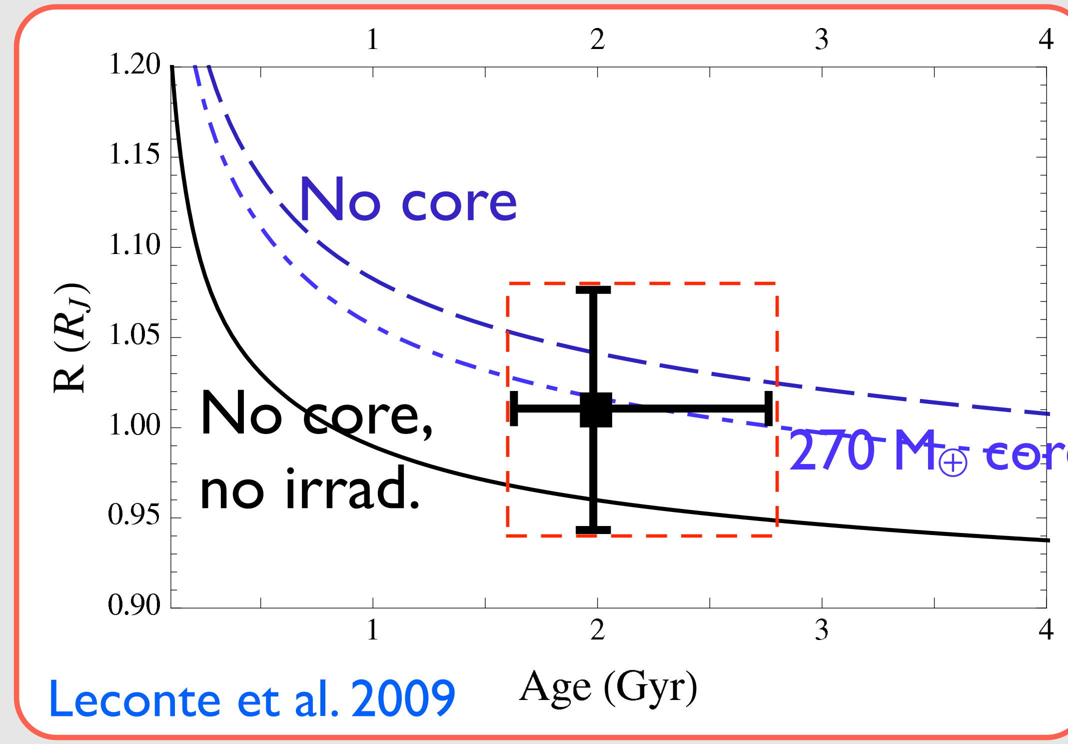
OBSERVATIONAL HINTS?

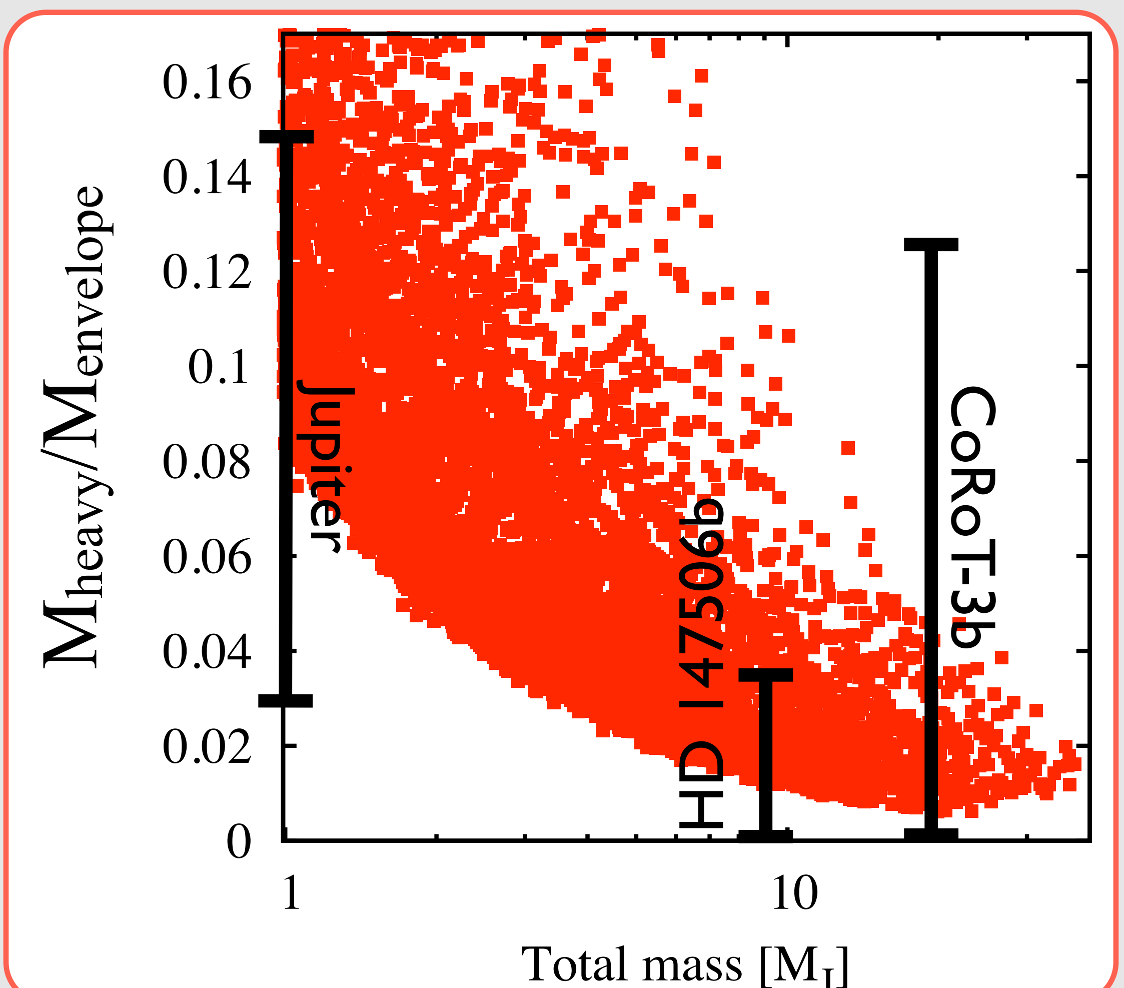
Hints I: Radius Constraints

HD 147506b (Hat P-2b): 9.04 M_J



CoRoT Exo 3b: 21.7 M_J

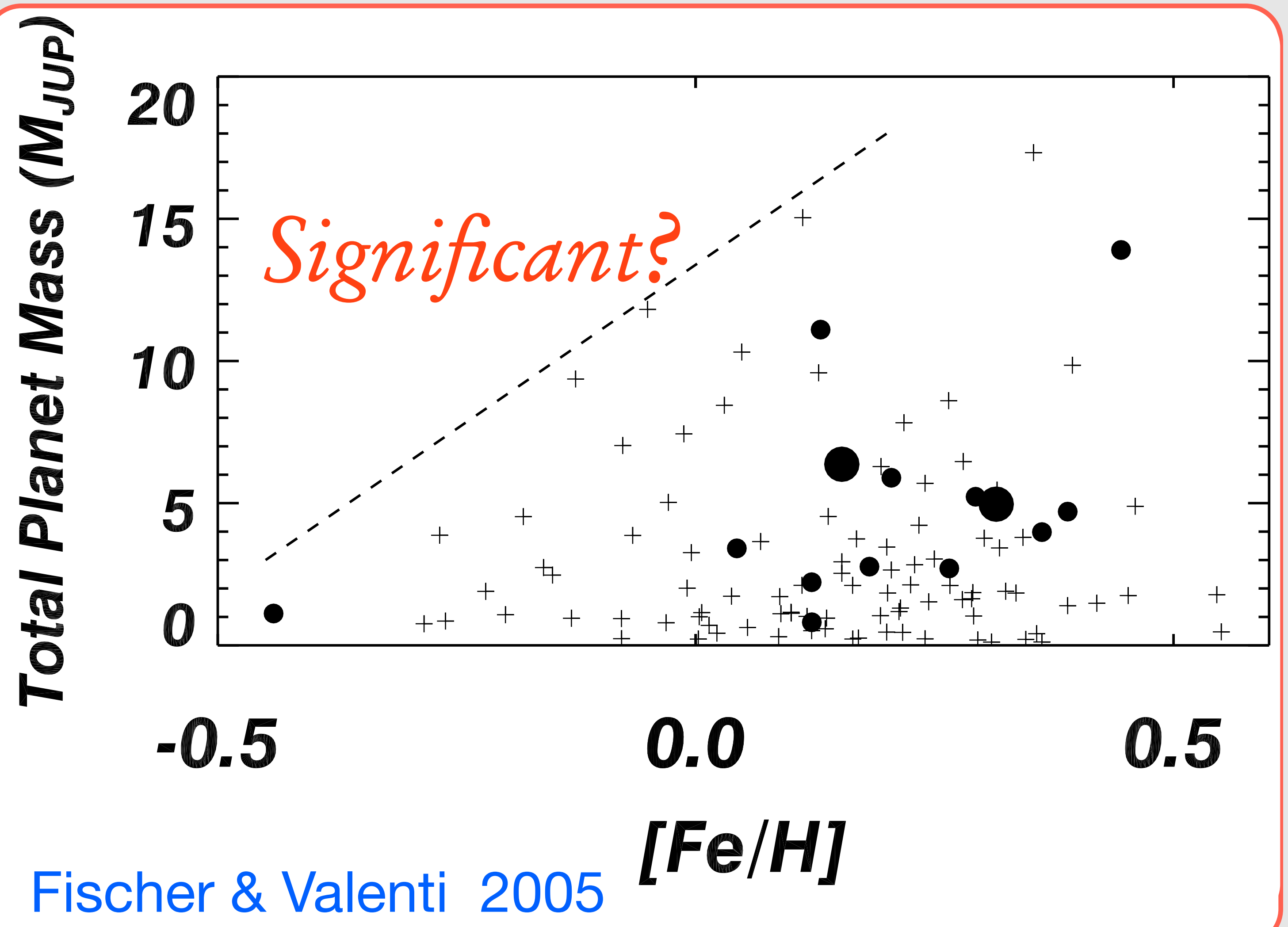




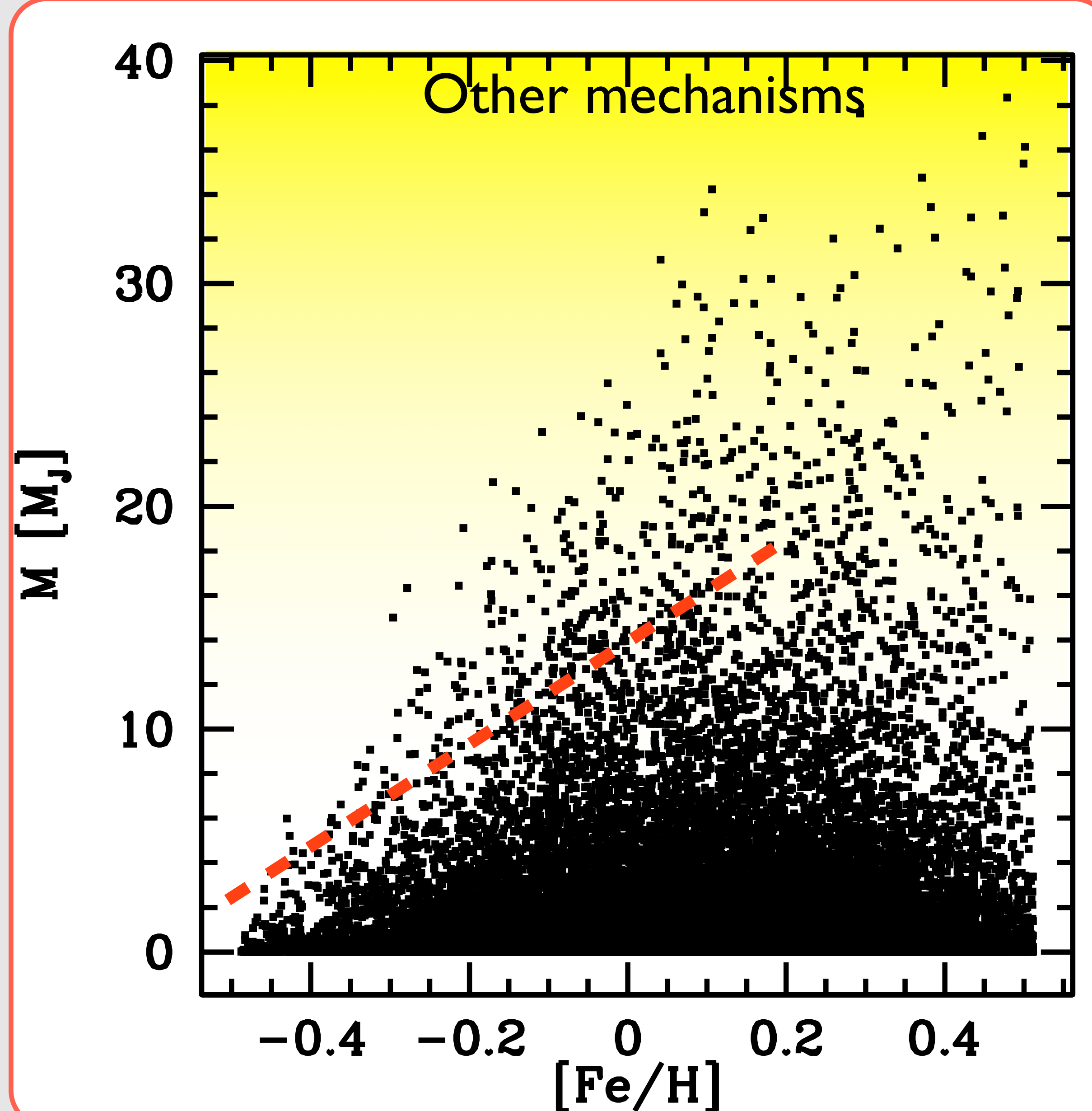
Problem: Relative enrichment goes down with mass: very large planets are very efficient in ejecting planetesimal (rather than accreting them). Maybe different for collision scenario (Baraffe et al. 2008).

Gets more difficult to distinguish.

Hints II: Metallicity Constraints



Synthetic population N= 100 000 (!)



Absence of very massive planets at low [Fe/H] around solar type stars.

Similar in model.

Not true for more massive stars.

Must build-up core very quickly.

Conclusions

- *Can disks form deuterium burning planets by core accretion?*
- *Yes, IF eccentric instability mechanism occurs.*
  - *Interesting class of new objects between planets and brown dwarfs.*
  - *Make the 13 M_J distinction even obscurer (cf. Chabrier et al. 2006)*
  - *Only if [Fe/H] > -0.2 , M_{disk} >3 M_{MMSN}, T_{disk}>2 Myr.*
  - *Inside 10 AU.*
  - *Rather low eccentricities e<0.25.*
  - *(Slightly) smaller radius than brown dwarfs.*
- *Deuterium burning: depending not only on total mass*
  - *Internal composition matters (a little bit).*
  - *D-burning delays decrease of luminosity for first ≈ 10 Myr (compared to contraction only).*
- *Slope of high mass end of planetary IMF.*
  - *Imprint of disk properties? (cf. core mass function - stellar IMF)*